Neutronic Characteristics of a Sodium-cooled Transmuter Charged with a Deep-Burn Discharge TRU Fuel

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1. Introduction

Fast spectrum reactors have several advantages in transmutation of the transuranic (TRU) nuclides : the nuclear fission produces more neutrons and the actinides have a higher fission-to-capture ratio than under a thermal spectrum. Meanwhile, General Atomics of the United States proposed a deep-burn concept, in which an ultra high burnup (over 60%) is pursued in order to incinerate the TRUs in a graphite-moderated, high-temperature, gas-cooled reactor (HTGR) without a costly repeated reprocessing and re-fabrication of spent TRU fuels.[1]. The deep-burn approach is based on the extremely high burnup potential of a ceramic-coated particulate fuel (TRISO). In HTGR, the graphite moderation produces valuable opportunities for thermal and epithermal neutrons to interact with fissionable and non-fissionable materials. HTGRs are allegedly known that a full TRU core is possible without compromising core safety features and thus a rapid TRU destruction is possible.

In this paper, a symbiosis of SFR and HTGR is considered and the neutronic characteristics of an SFR core charged with a TRU fuel from a deep-burn reactor (DBR). For a comparison purpose, a conventional TRU-loaded SFR is also considered.

2. Core Design and Performance Analysis

2.1 Description of Core Design

In this paper, a 600MWe (1523.4MWt) sodium-cooled fast reactor is selected as a reference design. In this design, void duct assemblies and a central island of non-fuel assemblies are introduced to reduce the sodium coolant void reactivity and to achieve power flattening under a single enrichment fuel. Figure 1 shows the configuration of the core. The active core height is 80cm at cold state and the outer diameter of fuel rod is 7.5mm. A fuel assembly consists of 267 fuel rods and six Ca_3N_2 rods. A 30 cm thick B_4C region (50wt% B^{10}) is placed below fuel to increase the neutron leakage. A uranium (U)-free fuel is considered to maximize the transmutation rate. The fuel form is TRU-W-28wt%Zr. Tungsten (W) [5,6] is introduced to improve the fuel Doppler effect because its temperature-dependent capture cross section ratios are similar to those of ^{238}U and its capture resonances are located between a few keV and 100keV. The theoretical density (TD) of fuel is assumed to be 12.52g/cm^3 and the smear density of 75%TD is used. Taking into account the fuel expansion, fuel density was reduced by a factor of 1.064.

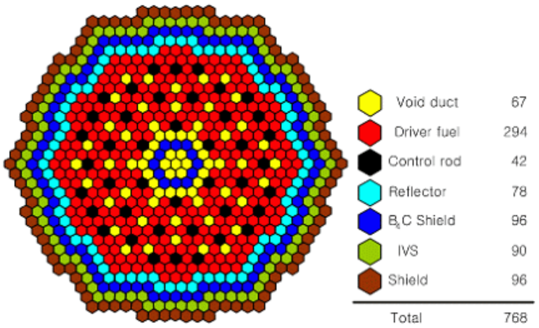

Figure 1 Configuration of the core with void duct assemblies

2.2 Core Performance Analysis

A REBUS-3 equilibrium model with a nine group cross section was used to perform the core depletion analysis. The cycle length is 332EFPD (11EFPM) and the refueling interval is 13months with a capacity factor of 85%. A five batch fuel management scheme is used and a 14-month cooling time is assumed. Table I compares TRU vectors from DBR and LWR. In Table I, it is noted that the discharged fuel from DBR has higher contents of ^{238}Pu, ^{241}Pu, ^{242}Pu, ^{243}Am, ^{244}Cm and a significantly lower content of ^{239}Pu than the discharged fuel from LWR. Table II shows the summary of the core performance analysis results. From Table II, the followings are observed; 1) the core with a DBR feed composition (Design-I) has a much smaller (by ~1475pcm) reactivity swing than the core charged with a conventional LWR TRU (Design-II). This is because the feed composition of Design-I has a higher ^{238}Pu and ^{242}Cm contents. The neutron capture of ^{238}Pu leads to ^{239}Pu and the alpha-decay ($T_{1/2}$=163day) of ^{242}Cm to ^{238}Pu. 2) Design-II has a higher discharge burnup (by ~24%) than Design-I. This is because the discharged fuel from DBR has a smaller amount of fissile material than the one from LWR and so the Design-I core has a higher initial inventory of heavy metals. 3) The transmutation rates are almost the same for the two cores (~540kg/cycle). 4) The Design-II core has a more negative fuel Doppler coefficient than the Design-I core. This is due to the fact that the Design-II core has a higher content of Tungsten in fuel. 5) Design-I show a higher sodium void worth than Design–II. The relatively high sodium void worth in the two designs is due to the fact that the Tungsten absorbs preferentially the low energy neutrons. That is to say, a spectrum hardening by a sodium coolant voiding leads to reduction of the neutron absorption. 6) The Design-I core has a higher value of delayed neutron fraction than the Design-I core because the delayed neutron is produced at lower energy (~500keV) and the Tungsten absorbs preferentially the low energy neutrons.

Table I Comparison of the feed fuel compositions

Nuclides	DBR discharged fuel	LWR discharged fuel
Np-237	4.94	6.76
Pu-238	11.3	2.26
Pu-239	**3.89**	**50.79**
Pu-240	10.8	22.48
Pu-241	**20.4**	**4.34**
Pu-242	29.0	4.59
Am-241	1.7	7.28
Am-242m	0.1	0.02
Am-243	9.0	1.20
Cm-242	2.7	0.00
Cm-243	0.08	0.00
Cm-244	5.58	0.24
Cm-245	0.4	0.03
Cm-246	0.00	0.00

Table II Core performance comparison

Parameters	Design-I	Design-II
Average discharge burnup (MWD/kg)	204.9	269.8
Burnup reactivity swing (pcm)	4718 (16.4$)	6193 (26.2$)
Average TRU conversion ratio	0.4891	0.3966
Peak fast neutron fluence (n/cm^2)	$4.03\text{x}10^{23}$	$3.908\text{x}10^{23}$
3D power peaking factor (BOEC/EOEC)	1.410/1.373	1.372/1.326
Average linear heat generation rate (W/cm)	233.4	233.4
Average volumetric power density (W/cc)	256.7	256.7
TRU consumption rate (kg/cycle)	546.5	543.8
Fuel Doppler coefficient (BOEC)	$-6.63\text{x}10^{-7}$	$-1.04\text{x}10^{-6}$
Radial expansion reactivity coefficient (pcm/%, BOEC)	-645	-656
Axial expansion reactivity coefficient (pcm/%, BOEC)		
Fuel	-229	-199
Fuel + structure	-166	-156
Sodium void worth ($)		
BOEC/EOEC	8.9/9.9	6.1/6.8
Effective delayed neutron fraction (BOEC)	0.00287	0.00236
Heavy metal (kg, BOEC)	11193	8249
W wt% in Heavy metal+W (BOEC)	9.58	33.33

3. Conclusion

The core performances of a sodium-cooled transmutater charged with a deep-burn discharge TRU fuel has been analyzed and compared with those of a conventional LWR TRU vector. The DBR discharged fuel feeding core has a much smaller burnup reactivity swing, a larger delayed neutron fraction but a smaller discharge burnup, a larger sodium void worth, and a less negative fuel Doppler coefficient than the LWR discharged fuel feeding core. The current study is based on an SFR design optimized for a LWR TRU feed. A core optimization is required for the DBR TRU feed case.

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